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SOLID MODELING AT THE US ARMY BALLISTIC RESEARCH LABORATORY

Paul H. Deitz

October 1984

US ARMY BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

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In this report, the requirement to accomplish solids modeling at the Ballistic Research Laboratory is examined. The historic need for solids file generation is discussed, and the present technique called COMGEOM is described. We discuss an interactive editor (GED) which has recently been brought on line. Finally, some requirements of an advanced modeler in the CAD/CAM arena are proposed.

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I. INTRODUCTION

One of the mission areas of the Ballistic Research Laboratory (BRL) is the vulnerability/lethality (VL) assessment of modern weapons systems. Vulnerability is viewed from the standpoint of a target under attack: Given a particular bullet, how survivable is a specific helicopter? The study of lethality examines the reciprocal problem, how damaging is a given attack mechanism to a particular target? Classically, vulnerability/lethality analyses were strictly examinations of target/bullet interactions. Today VL studies impact a far wider range of materiel analyses including nuclear effects, mechanical design, and electromagnetic signature prediction.

Decisions concerning weapons systems procurement at nearly every turn of the R&D cycle are fed by computer-based assessment programs: The questions are always how heavy, how strong, how expensive, how lethal? Every analytical code used to answer such a question is driven by geometry. Thus the complete three-space definition of materiel is a critical input to analysis codes. In the current parlance, the generation of complete and unambiguous geometry in three space is known as solids modeling.

This paper will discuss the importance of solids modeling to the pursuit of the BRL mission, the recent improvements we have made in our ability to handle the generation and display of geometry, and our view of the future of solid modeling to the Department of Defense arena.

II. BACKGROUND

The history of VL analysis goes back more than 30 years to the first studies of aircraft survivability. It was recognized that the vulnerability of an aircraft was clearly a function of design - the strength of materials, the redundancy of systems, the robustness of critical components. In this period, most VL analyses were done "after-the-fact," that is, systems were fielded, and vulnerability analysts attempted to increase materiel survivability gradually through system upgrades. During this time VL assessments were made by hand using engineering drawings. Calculations were made manually to infer the projected thicknesses of material and the presented areas of particular components.

During the mid 60's, Mathematical Applications Group, Incorporated (MAGI) was enlisted to generate a suitable technique for automating these processes. This early work[1,2] resulted in a geometric description technique known as combinatorial geometry (COMGEOM). This method,

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[1] "A Geometric Description Technique Suitable for Computer Analysis of Both Nuclear and Conventional Vulnerability of Armored Military Vehicles," MAGI-6701, AD847576, August 1969.

[2] "The MAGIC-SAMC Target Analysis Technique," Vol VI, AMSAA TR14, April 1969.

described in more detail in the next section, uses generic geometric shapes, or primitives, as building blocks. Material is defined everywhere within these primitives; hence the term "solid modeling." Thus COMGEOM, together with a ray-tracing program used to simulate bullet trajectories[3] came to be used as the standard Army description technique for geometric input to VL analyses. The COMGEOM technique also formed the basis of MAGI's Synthavision[4] code which incorporates sophisticated rendering algorithms.

It is worth noting that while the Army's geometric requirements in VL were being served by COMGEOM, an entirely different approach was utilized by the Navy and Air Force. PATCH, a surface description technique, was developed by Falcon Corporation; it uses triangular surface patches to envelope completely a volume. By this method, geometric information is handled as explicit surfaces in a polygonal boundary representation. In the vulnerability community there was much debate as to the relative merits of each approach; a considerable number of target descriptions were generated by both methods, resulting in needless duplication of effort. Recently interface (shotline) codes have been written[5] so that descriptions by either method of construction can be used in any analysis program.

III. THE COMGEOM TECHNIQUE

A COMGEOM data base consists of three related tables: the first of these specifies the fundamental geometric constructs, or primitives, used. Figure 1 shows the first group of primitives. These are polyhedrons with from four to eight vertices. Figures 2-4 show the classes of general truncated cylinders, ellipsoids, and toruses, respectively.

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[3] MAGIC Computer Simulation, Vol. 1, User Manual, 61JTCG/ME-71-7-1, July 1971. MAGIC Computer Simulation, Vol. 2, Analysts Manual Parts 1 and 2, 61JTCG/ME-71-7-2-2, May 1971.

[4] R. Goldstein and L. Malin, "3D Modeling with the Synthavision System," Proc. 1st Ann. conf. on Computer Graphics in CAD/CAM Systems, Cambridge, Mass., pp. 244-247, April 9-11, 1979.

[5] K. A. Applin, "Utilization of PATCH/Triangular Target Description Data in BRL Internal Point Burst Vulnerability Assessment Codes," USABRL Memorandum Rpt. ARBRL-MR-03048, Aug 1980. AD# B051489L

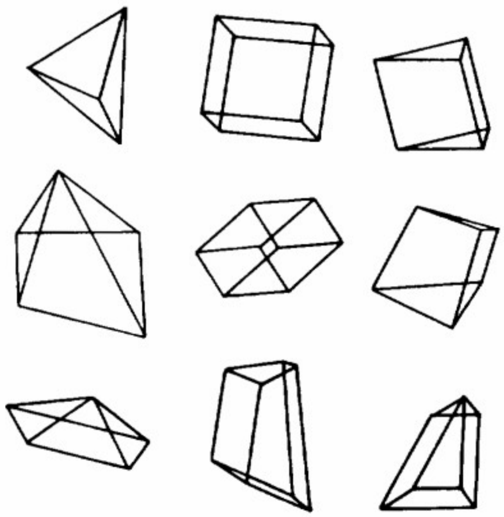

Figure 1. The Polyhedron Primitives Exhibiting From Four to Eight Vertices (ARB4-ARB8)

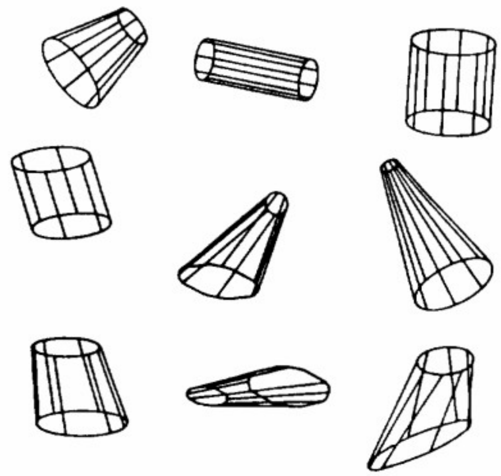

Figure 2. The Primitive Class of the General Truncated Cylinder (TGC)

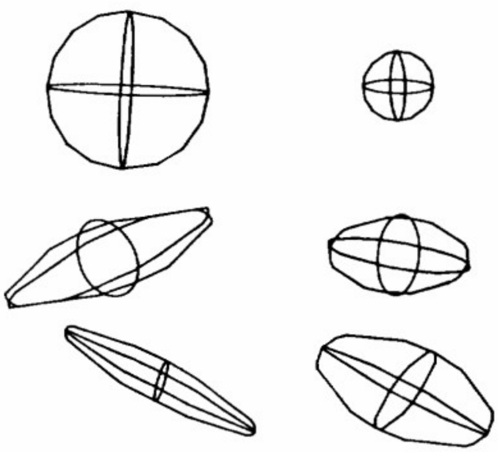

Figure 3. Examples of the Ellipsoid (ELL)

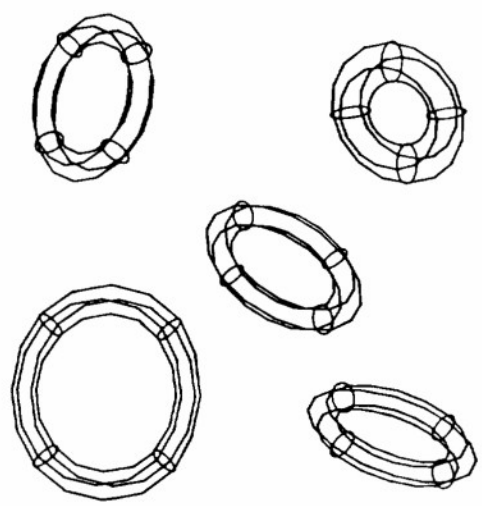

Figure 4. Examples of the Torus (TOR)

Finally, Figure 5 illustrates an example of the most general primitive method used by the BRL, an Arbitrary Surface. This construct is formed of a set of connected planar patches, and is functionally equivalent to the PATCH boundary representation mentioned above.

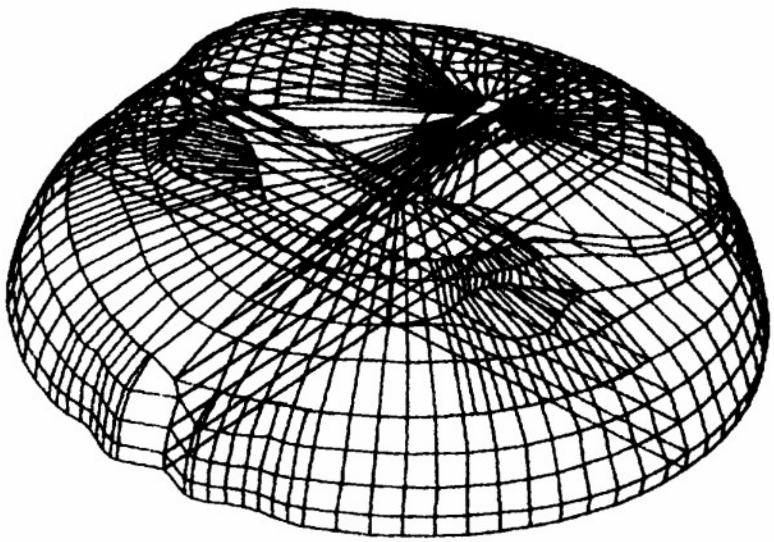

Figure 5. An Example of the Most General Primitive Used in GED, the Arbitrary Surface (ARS)

The construction of COMGEOM descriptions involves the specification of the primitives together with Boolean operations if two or more such primitives overlap. The Boolean operations are defined in Figure 6 and include the Intersection, Difference, and Union. Objects are assembled by defining various primitives and their logical relationships.

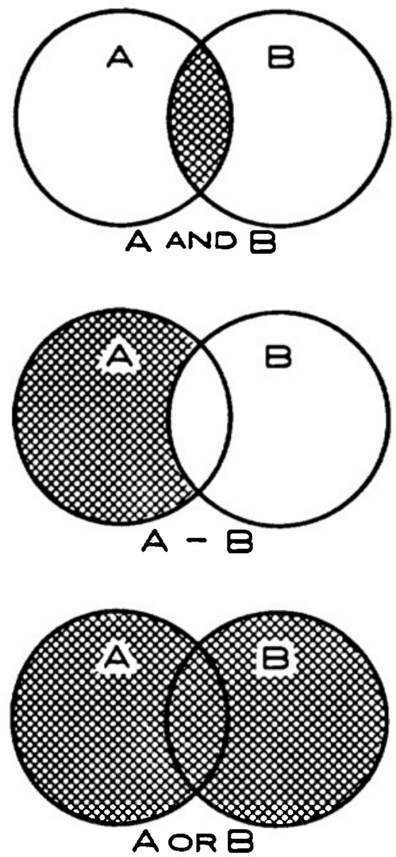

Figure 6. Three Venn Diagrams illustrating the logical operations permitted between primitives (from top to bottom): the intersection, the difference, and the union.

Finally, a third table is used to define the material composition of given objects. An example of the three listings is replicated in Figure 7 for a simple fuel tank. The top block shows the object (fuel tank) represented by three ARB8s (boxes). The first ARB defines the outside of the tank, the second the inside, and the third the fuel, which occupies the bottom section of the tank. The second block indicates the Boolean operation in which the second ARB is subtracted from the first to define the actual tank thickness. Finally the third block defines the material makeup of this object.

547arb8	-70.000	-21.000	-20.000	-70.000	21.000	-20.000
547	-70.000	27.000	-10.000	-70.000	-27.000	-10.000
547	-104.000	-21.000	-20.000	-104.000	21.000	-20.000
547	-104.000	27.000	-10.000	-104.000	-27.000	-10.000
548arb8	-70.250	-20.750	-19.750	-70.250	-20.750	-19.750
548	-70.250	26.750	-10.250	-70.250	26.750	-10.250
548	-103.750	-20.750	-19.750	-103.750	-20.750	-19.750
548	-103.750	26.753	-10.250	-103.750	26.750	-10.250
549arb8	-70.250	-20.750	-19.750	-70.250	-20.750	-19.750
549	-70.250	23.750	-15.000	-70.250	23.750	-15.000
549	-103.750	-20.750	-19.750	-103.750	-20.750	-19.750
549	-103.750	23.750	-15.000	-103.750	23.750	-15.000

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•
•

547	547	-548	fuel tank
548	548		air
549	549		fuel

•
•
•

547	219	05	fuel tank
548	220	05	fuel tank air
549	299	05	fuel

Figure 7. An Example of a COMGEOM Listing for a Simple Fuel Tank The top listing defines the primitive class.

It can be seen that it takes roughly 100 numbers to specify a simple box, partially filled with fuel. Were the box to be modified in any way, translated, scaled, or rotated -virtually all of the defining numbers would have to be changed.

IV. THE BOTTLENECK

Until recently all target descriptions at the BRL were built by explicit manipulation of numbers such as shown in Figure 7. All matrix operations for scaling, translation, and rotation were computed off-line, reentered into the code by hand, and sent to a mainframe for batch processing. Hours later, the results of an operation could be verified by means of a hardcopy graphics plot. The implication of such a modus operandi can be appreciated by inspection of Table I.

Table 1. Typical COMGEOM file sizes. Ranges of numbers represent the number of regions (objects) composing BRL target descriptions.

Low	300-500
Average	1000-2000
High	2000-3500

It should be clear why detailed target descriptions have taken as much as eighteen months to generate. It should also be apparent that the inability to generate geometry in a timely fashion implies that applications codes which are dependent on geometry for input are of little value in real-time development cycles which have sharply defined windows within which actual system design can be influenced.

Because of this operational bottleneck, the BRL in early 1980 initiated a program to improve the response time of the target description process through the application of interactive graphics techniques. Initially, we expected to find a commercial editor which would meet our requirements. However, after a detailed scrutiny of market offerings, we could not identify an interactive modeler with the appropriate characteristics. Hence, we embarked on an internal project to develop an interactive COMGEOM editor[6] to serve our interim needs while continuing to define the requirements for an advanced modelling capability.

V. THE GRAPHICS EDITOR (GED)

By way of background, GED is written in C code and runs under UNIX.* UNIX has come to mean both an operating system as well as an accompanying set of system utilities. The development of GED represents only one of many elements in a BRL program which has been established to create a broad-based automated office environment. There has been a proliferation of more than a dozen minicomputers, all running UNIX, all networked together, tied to the mainframes (CYBER machines), and linked to the DARPA network (ARPANET). Such an approach has given us relative robustness (due to the user load being distributed over many machines), relative vendor independence (due to the portability of UNIX), and local CPU support (the CPUs are located where the high-bandwidth graphics displays are used). Because of the connectivity of the UNIX machines, users with applications codes can access those particular machines upon which are resident the primary files generated in GED.

[6] E. P. Weaver and M. J. Muuss, " Interactive Graphics for Display and Modification of Target Descriptions - A Feasibility Study," BRL Report in preparation.

*UNIX is a Trademark of Bell Laboratories.

Presently GED runs on both DEC PDP 11/34s and PDP 11/70s. The displays used for interactive manipulation of target descriptions are Vector General (VG) vector display stations. The code is now being ported to a Megatek raster display.

GED[7] uses an internal data structure which is hierarchical in nature, with each node or position in the hierarchy occupied by an object. An object is the GED basic data unit and is defined as either a solid (primitive) or a combination of solids. A solid is one of the generalized COMGEOM primitive types (shown in Figures 1-5), while a combination is a group of objects. Each member object of a combination has a transformation associated with it. Any object not at the top of a hierarchy is referenced by (is a member of) a previous combination and each such reference has an associated transformation. The bottom object of every hierarchy path is a solid. This hierarchical data structure allows actual subsystems of a target to be grouped together and edited as a unit.

Figure 8 illustrates the GED design. On the left is represented a standard COMGEOM listing. A code called CVT (for convert) transfers the COMGEOM listing into the internal format of GED. This internal format is a superset of the standard COMGEOM listing. During the convert operation, a simple hierarchical structure is achieved automatically, but user interaction is required to place various objects/solids in appropriate branches. The parts bin represents on-line storage in which not only the generic primitives reside, but a series of graphics data bases of many descriptions, whole and in individual components. The time required to build new descriptions is greatly reduced due to this on-line "parts shelf." Upon completion of a design session, the program DECK converts the GED format back to a standard COMGEOM (card image) deck for subsequent processing by the applications codes. Associated with DECK is a program called VIEW. This terminal-independent graphics package makes it possible to view COMGEOM images on distributed graphics terminals remote from the CPU.

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[7] M. J. Muuss, K. A. Applin, J. R. Suckling, G. S. Moss, E. P. Weaver, and C. A. Stanley "GED: An Interactive Solid Modeling System For Vulnerability Assessments," BRL Technical Report, ARBRL-TR-02480, March 1983, (UNCLASSIFIED). AD# A126657

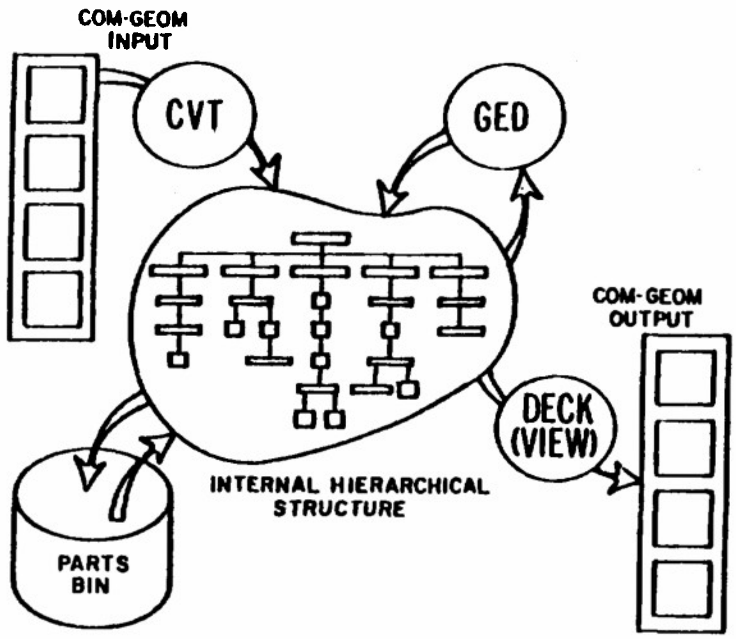

Figure 8. A Diagram of the GED Design. A code called CONVERT (CVT) transforms the standard COMGEOM deck into the hierarchical format of GED. There the graphics files may be edited and new graphics files included from on-line storage (via the "parts bin"). At the close of an editing session, the modified GED file is converted to COMGEOM-compatible card images or transformed through the program, VIEW, for display on distributed graphics terminals.

There are, of course, two principal functions of GED: the first is viewing COMGEOM files. The standard capabilities of zoom, slewing, and rotation are initiated by user manipulation of the keyboard, push buttons, joy stick, and tablet. An angle-distance cursor can be called up to aid in measuring absolute and relative distances and angles. Through a series of simple keyboard commands, any portions of a target description can be brought into view from any angle/distance; a cutting plane may be used to intersect the displayed images. This plane, oriented parallel to the face of the CRT, can be moved in the z axis. All portions of the display between the plane and the viewer are removed. All solid objects are represented as wire frame figures. No hidden lines are removed.

In terms of actual editing, all the standard features are realized including the ability to display any or all of the graphics data base. The user may traverse the hierarchical tree at will and apply solid-specific editing to any given solid at the ends of the tree (leaves). He may also traverse higher and apply the operations of scaling, rotation, and translation to objects (collections of primitives). The hierarchical tree may be regrouped in any fashion, and the Boolean operations and materials redefined. A menu can be toggled on or off as needed to choose appropriate editing operations or to define the tree path to a specific primitive.

Figure 9a and 9b illustrates an editing operation with a simple graphics file. Figure 9a shows a COMGEOM file as displayed in GED at the start of an editing session. Figure 9b shows the corresponding file when processed by a batch program known as GIFT[8,9] GIFT is used not only to generate such pictures, but also to generate the shotline data used in subsequent vulnerability codes. Hidden lines are clearly removed. Figure 10a shows the results of a simple editing operation. The engine of the vehicle has been moved out of the armor shell and the driver has been moved forward and up. These two operations would entail at most a few minutes of time to accomplish. Figure 10b gives the GIFT-processed view of the edited vehicle.

It should be emphasized that GED runs on small 16-bit mini-computers. In fact, we expect to implement soon a PDP 11/34 configuration in which two vector refresh terminals are supported, each running the GED program. At this time, GED has been used in production about five months. Preliminary results point to a productivity enhancement of from five to eight using GED over previous techniques.

VI. A WIDER VIEW

If the generation of geometry is strictly for application to VL analyses of the classical bullet/target interactions, then COMGEOM is demonstrably adequate. For the vast majority of ballistic calculations, extreme fidelity of geometry is not required. The physics of penetration is too poorly known to require geometric detail to an accuracy of a few degrees or a few millimeters. However even now, VL studies are pushing into such areas as electromagnetic signature analysis and suppression. Clearly, solar reflection, for example, from the canopy of an aircraft cannot be properly simulated by means of a gross conglomerate of (planar) surface patches. Because of ever-widening requirements of analysis, geometry is often needlessly replicated for input to a diversity of analysis codes.

In the development of materiel, geometry forms the common thread from concept definition through manufacturing. Also geometry should be portable among DOD agencies and beyond to vendors. It is now the exception for developers of new weapons systems not to accomplish concept definition by means of interactive graphics. Unfortunately however, the majority of vendors now generate geometry which is capable of little more than supporting visualization and drafting functions; the basic files will not support analysis codes of the kind discussed here because of the incompleteness of the data base. Such "wire frame" representations have little value in the area of rigorous analysis of design.

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[8] L. W. Bain, Jr., and M. J. Reisinger, "The GIFT Code User Manual; Volume I, Introduction and Input Requirements (U)," BRL Report No. 1802, July 1975. AD# B0060371.

[9] G. G. Kuehl, L. W. Bain, Jr., M. J. Reisinger, "The GIFT Code User Manual; Volume II, The Output Options (U),"USA ARRADCOM Report # 02189, Sep 79, AD# A078364.

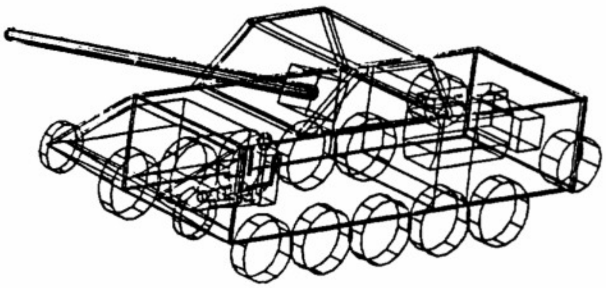

Figure 9a. A Simple Graphics File Illustrating the Kind of Image That Might be Viewed and Edited Interactively via GED.

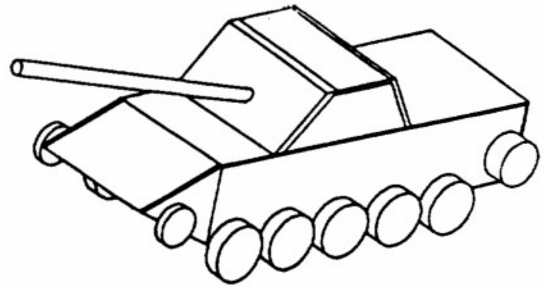

Figure 9b. The Corresponding GIFT-Processed Picture

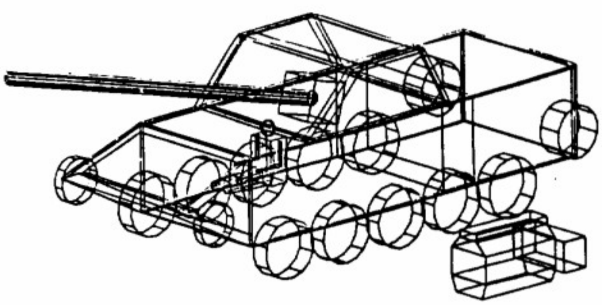

Figure 10a. Two Editing Operations Have Been Accomplished. The Engine Has Been Moved Out of the Vehicle, and the Driver Has Been Moved Forward and Up.

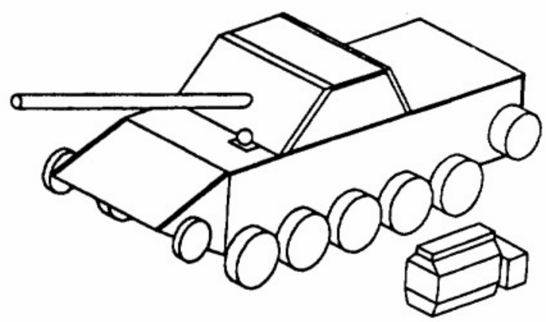

Figure 10b. The Resulting GIFT-Processed Pictures.

We suggest that the generation of "robust" geometry, that which is capable of defining material in three space, and the ability to exchange that geometry, both within and outside of the originating organization are the keys to future benefits in productivity.

VII. REQUIREMENTS FOR AN ADVANCED MODELER

The problem of generating geometry for input to VL models is actually one of computer-aided design. And because we view vulnerability/lethality assessment as a subset of the larger computer-aided design/analysis problem, we think it important to consider the requirements of geometry in a more global sense. There are three principal issues:

A. Geometry

- The modeler must be capable of true three-space definition of material in order to support follow-on analysis models, i.e., it must have a solids capability. This requirement has been emphasized throughout this paper.

- The modeler must support complex surface geometries defined to an arbitrary level of precision. This is a natural consequence of the increasing sophistication of analysis models. It is well known that for certain electromagnetic scattering models geometric detail done to the order of the wave length of the radiation is required. And in the manufacturing domain, there are many objects which require essentially free- form surface capability. COMGEOM, as used by the BRL, is restricted to planar (or planar-faceted) objects and quadratic surfaces. PATCH is restricted to polygonal patches.

- It must be possible to edit the surface geometry of an object directly. This ability is important for many applications in which local detail must be modified. A designer thinks in terms of physical interfaces, not arbitrary mathematical constructs. This is why the display should prompt the user in terms of surface structure and the method be capable of direct surface modification. This is a serious limitation of the COMGEOM approach. Since the primitives appear without logic processing (e.g. Figures 9 and 10a), the geometry is referred to as "unevaluated".[10] It can be seen from Figure 6 that just two overlapping primitives can be interpreted in at least four distinctly different ways. As more primitives are added to describe an object, the interpretation can get far more ambiguous.

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[10] A. A. G. Requicha and H. B. Voelcker, "Solid Modeling: An Historical Summary & Contemporary Assessment," IEEE/CS Computer Graphics & Applications, March 1982.

- The modeler should support the definition of predesigned shapes (primitives) and through Boolean operations support refined objects. The Boolean capability is important, for example, in construction of complex surfaces in which one face may generally lie within the other. The locus of intersection can then be computed. This property also makes it possible to manipulate geometric features (e.g. the hole diameter in a mechanical part) in a parametric fashion. Often, the initial stages of model building are accomplished far more quickly by using generic primitives. But the final phases are impeded, however, when the user is constrained to the degrees of freedom of the primitive.

- The modeler should be capable of displaying evaluated geometry (i.e., the actual physical surfaces should be rendered),but the modeler should not carry the geometry explicitly in terms of the physical surfaces themselves. A classical approach to modeling objects has been to effect a discrete sampling of the surfaces of the object itself. This is the approach used in PATCH, and it requires an initial choice of the sampling interval or size of the surface patch. In addition to being highly inefficient in terms of required data storage, this approach suffers from two serious problems: 1) the size of the surface patches are often inappropriate for an intended application. For example, if the object is far from the observer, much mathematical manipulation must be accomplished even if the detail cannot be resolved. And at the other extreme, either for viewing up close or other processing, the size of the surface patches may be too gross for the application, and 2), editing so many individual patch parameters is difficult.

- The modeler must have real-time response to interactive commands, and should display geometry in an unambiguous fashion. This is an operational constraint which also reflects on statement 3.

B. Attribute Capabilities

- There must be a data base structure by which object properties can be tied to geometry. This property is critical for follow-on analysis codes which require physical properties, identifying stock numbers, emissivities, and so forth.

C. Portability

- There must be defined a neutral files structure so that geometry generated by different modelers can be exchanged and utilized. It is critical that the mathematical basis for geometric description (as well as other complex structures and relationships) and the ability to share that geometry be accomplished in a vendor-independent fashion. Currently this goal is being pursued by a series of parties within and outside of the government. The group, under the title of

Initial Graphics Exchange Specification (IGES),* is attempting to set forth a specification for the transfer of traditional design data between non-homogeneous systems. The goal is to write an interface (translator) between each proprietary graphics data base and the neutral IGES file. The IGES file could then be transferred between different users and then translated back into the format of the new user.

VIII. A CANDIDATE MODELER

A candidate solid modeler has been found that provides many of the desired capabilities mentioned above. The modeling method, called Alpha_1[11] is being developed at the University of Utah. The method uses discrete B-splines for surface definition which provides for easy modification to the surface structure, even when compound shapes are concerned. This property is achieved through a closed-form relationship between the underlying spline architecture and the surface structure which it describes. An important advantage of this approach is that surface geometry can be modified through the manipulation of of a discrete number of control points; however, the surface structure can be defined (calculated) to an arbitrary level of precision. Hence surface information can be computed optimally for a given application, be it an image calculated for a particular set of perspective/object/display characteristics or for a given machining operation.

Alpha_1 has already demonstrated the capability to handle complex geometric structures. Figure 11 illustrates a model of an engine bulkhead. Figure 12 shows the same model in closer detail. Alpha_1's self-optimizing rendering algorithm makes it possible to zoom arbitrarily close without picture "break up." This capability is achievable because the surface geometry is analytically related to the spline structures and has been recomputed to a level of refinement appropriate to this specific viewing perspective.

Figure 13 shows Alpha_1's sculptured-surface capability in an airfoil section of a turbine blade part. Finally using another display option, a transparent rendering depicting the relationship of the interior cavity to the rest of the part is shown in Figure 14. These

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*The specification is based on part on both Boeing's CAD/CAM Integrated Information Network and General Electric's Neutral Data Base. The IGES specifications have been accepted as the ANSI standard for the Digital Representation for Communication of Product Definition Data. Vendors have already produced translators to/from the communication file and their internal data base. Although IGES standards are established for to/from the communication file and their internal data base, although IGES standards in the solids area are just being formulated.

[11] E. Cohen, R. Lyche, R. Riesenfeld, "Discrete B-Splines and Subdivision Techniques in Computer-Aided Geometric Design and Computer Graphics," Computer Graphics and Image Processing, Vol. 14, No. 2, Oct. 1980, p.87.

Figure 11. Example of Aircraft Bulkhead Modeled and Rendered Using Alpha_1

Figure 12. Closeup of the Bulkhead Shown in Figure 11.

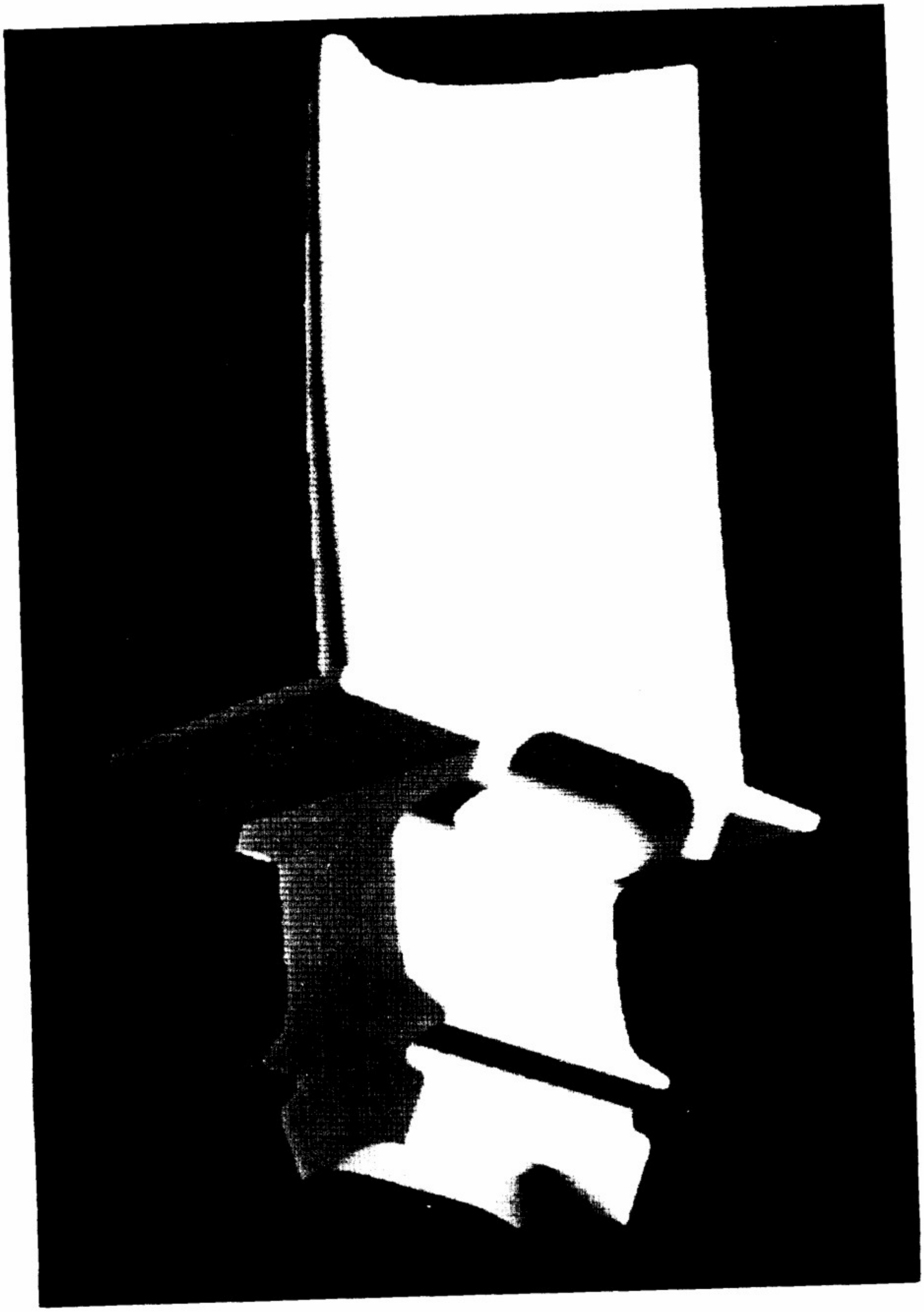

Figure 13. Turbine Blade Rendering Using Alpha_1 Solids Modeler

renderings are computer-generated from the actual geometry employing hidden surface and smooth shading algorithms.

IX. CONCLUSION

In this paper we have attempted to give a perspective of the solids modeling effort in the Ballistic Research Laboratory. Although our history is relatively mature in the area of solids, we see our requirements as lying in the general CAD/CAM area and thus not atypical of many industrial users.

The development of our solids modeler, GED, has made a substantial improvement in our ability to handle geometry. However, as this ability has grown, so has the sophistication and diversity of our application codes. If we step back to view vulnerability/lethality assessment as a subset of the larger computer-aided design/analysis problem, the requirement to handle complex geometries in a broad arena becomes crucial. We believe that it is possible to construct advanced modelers capable of meeting the challenge of complex geometries; that data base structures can be appropriately tied to the geometry to feed applications codes; and that portability can be achieved through computer networking and neutral files translation and transfer. It is only by achievement of these goals will the real promise of productivity enhancement through CAD/CAM be realized.

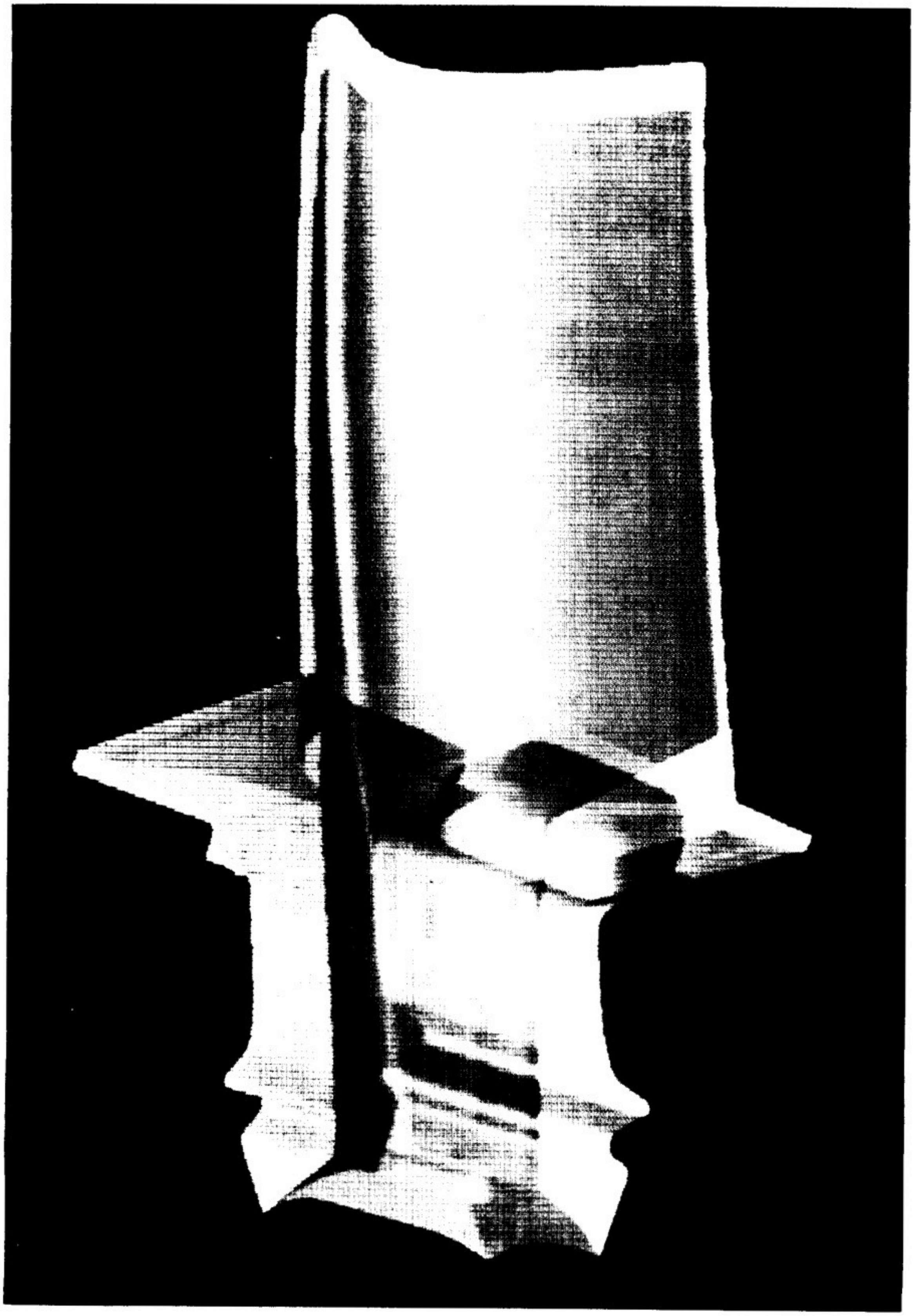

Figure 14. Turbine Blade, Interior Detail

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